Control and Stability Analysis for Grid-Connected Current Source Inverter with Digital Delay

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***Abstract*—This paper addresses a single-phase current source inverter (CSI) controlled by grid current. An inherent damping control method is proposed to suppress the system resonance by using reasonable delay. A transfer function model is developed first for studying the relationship between time delay and stability of single-loop digital control system. The delay stability region is calculated by transfer function model in s-domain. When the time delay is in the stable range, it is shown that the inherent damping characteristic of the system can suppress the resonance generated by the *CL*-filters without additional damping control. The close correlations between the simulation results and theoretical analysis demonstrate the effectiveness of the delay-dependent stability analysis.**

Keywords—current-source grid-connected inverters, CL-filter, digital control, inherent damping, resonance, time delay, stability analysis.

I. INTRODUCTION

In recent years, due to environmental pollution associated with fossil fuels and energy security issues, photovoltaic (PV) systems increasingly have taken into consideration [1]. Current research on the PV systems generally relies on the voltage-source inverter (VSI) because of its smaller power losses and familiar control. These inverters usually have a two-stage topology, which increases the circuit complexity and may reduce system overall efficiency [2]. An alternative way to achieve dc-ac inversion is one power stage topology of a CSI, which have the inherent current limiting capability and thus enhance the reliability [3]-[4]. In fact, the CSI have been used for PV system in the last decades [5]-[7]. In [8], the advantages of CSI over VSI topology is given.

To make the power quality of current source grid-connected converters injected into the grid meet the requirements of IEEE 519-1992 and IEEE 1547-2008, a *CL*-filter should be inserted on the ac side to reduce current harmonics [2]. However, the grid-connected inverters are in an undamped and unstable state due to the inherent resonance peaks of the *CL*-filters, regardless of the controller used for direct output current control. The resonance peak of the filter can be suppressed by modifying the filter hardware structure or improving the grid-connected control strategy, which are called passive damping [9] and active damping [10- 13].

Compared to passive damping techniques, active damping techniques introduce lower power loss and reduced size and cost, due to the absence of actual resistors [14]. However, it will increase the complexity of control algorithm [15]. A virtual *RL* damper is proposed in [1], the active damper suppresses the current oscillations and mitigates the harmonic currents via increasing the damping ratio and raising the natural frequency. To suppress the *LC* resonance in the current source inverter, active damping method using virtual harmonic resistor is adopted. AC-side instability of grid-connected CSI-based PV systems has been addressed in [13] and virtual *RC* damping technique has been proposed. However, time delay of the virtual impedance loop due to computation and PWM will affect results in a less stable system [16]. [14] employs a virtual negative inductance at the resonance frequency in parallel with the filter inductance, resulting in a larger inductance, impeding harmonics. It is straightforward, but the effect of time delay is ignored, and thus it might not be effective for digital control [17]. Active damping is the state-of-the-art solution to this problem [1]. However, none of the above control methods considers the effect of delay time on the control effect.

The damping performance will be affected by the inherent time delay of digital control, especially for high power low switching frequency applications [18]. While many active damping methods have been proposed to overcome the resonance issue, the role that delay plays in the effectiveness of these strategies is still not fully resolved. In the digitally controlled system, the inherent computation delay will change system phase-frequency characteristic and thus may affect system stability. Nowadays the effect of delay on system stability has been widely concerned by researchers, but the studies remain concentrate on voltage source converters with *LCL*-filters [17-19]. With the widely use of current source converters, the effect of delay on system stability should also be studied in depth.

In this paper, an analysis on the stability impact of the time delay is presented for grid-connected CSIs. Section II studies the system model and an analysis of the relationship between the time delay and system stability. System stability based on grid-side current control are evaluated in continuous domain. Moreover, the proposed stability theory under weak grid condition is analyzed, and it is proved that the proposed control strategy has a certain adaptability to the weak grid case. In Section III, the delay-dependent stability research has been validation and evaluated through simulation on single-phase current source inverter. It is shown that if the delay and the resonant frequency are within the stable range, CSI can be

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stabilized without adding additional active damping controls and complex calculations, which is simple to implement.

II. Stability Analysis Based on Time Delay

A. Transfer Function of Single-phase CSI

Fig. 1 shows the circuit diagram and control system of a single-phase CSI, where a *CL*-filer is connected to the grid at the ac side. $S_1 \sim S_4$ are an IGBT and a diode in series. In practice, the RB-IGBT can also be used to reduce switching losses and increase the system efficiency [20].

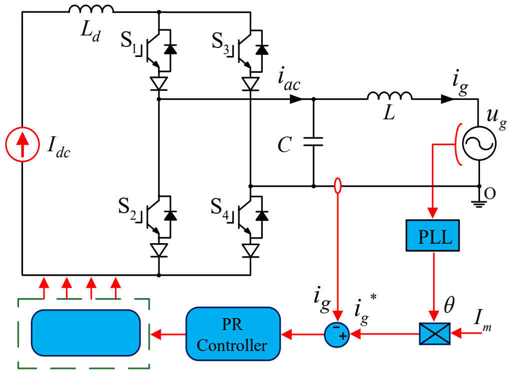


Fig. 1. Circuit diagram and control system of current source converter.

The grid current i_g is controlled by a closed loop so that its amplitude can reach the current reference value. The current control is realized with a Proportional + Resonant (PR) controller while a Proportional + Integral (PI) controller would result in large static error of grid current [21].

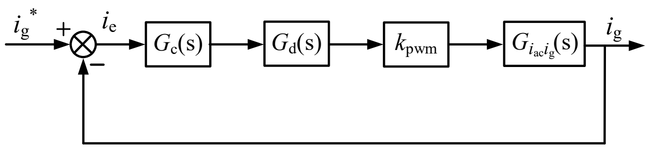


Fig. 2. Control block diagram of current source grid-connected converter in the continuous *s*-domain

The effect of the delay on the digitally controlled inverters can easily be studied in s-domain [17]. Considering the delay, the control block diagram of the current source grid-connected inverter in the continuous s-domain is shown in Fig. 2, where $G_c(s)$ is the current controller, the expression of $G_c(s)$ is

$$G_c(s) = k_p \tag{1}$$

where k_p are the proportional gain of the current PR controller. (The resonance gain has small influence above 50Hz as per, and the effect of resonant controllers on the dynamics and stability are negligible [22]). Since the switching frequency of the CSI is much higher than the grid operating frequency, function of CSI is represented as a linear gain k_{pwm} [18] and expressed as $k_{pwm}=I_{dc}$. $G_{i_{ac}i_g}(s)$ is the transfer function from the grid side current i_g to the inverter side current i_{ac}. The expression of $G_{i_{ac}i_g}(s)$ is

$$G_{i_{ac}i_g} = \frac{i_g(s)}{i_{ac}(s)} = \frac{1}{LCs^2 + Crs + 1} \tag{2}$$

where r is the parasitic resistance associated with the inductor.

The definition of delay time in a digital control system is the sum of computation and PWM delays. The transfer function of total time delay in the control loop can be expressed as

$$G_d(s) = e^{-sT_d} \tag{3}$$

where T_d is the total time delay expressed as $T_d = (\lambda + 0.5)T_s$. λ is the delay coefficient, which can take any value in the following analysis.

According to Fig. 2, the open-loop gain of the grid-side current control is

$$T_g(s) = k_{pwm} k_p e^{-sT_d} \frac{1}{LCs^2 + Crs + 1} \tag{4}$$

B. Stability Analysis and Cauculation of Delay Stable Range

Stability analysis is carried out by means of the Nyquist stability criterion. When $T_d = 0$, the phase falls from 0° to -180° , and the system is unstable. Then with the increase of T_d, the phase angle at high frequencies is shifted downward. When $T_d = 3\pi/2\omega_{res}$, the phase does not cross the - $(2k+1)\pi$ ($k = 0,1,2...$) line in the magnitude of bode diagram > 0 dB region, the system can be stable. However, the system will be unstable if the delay time is too high. For example, when $T_d = 2\pi/\omega_{res}$, the system goes unstable again. Thus, there must be a reasonable T_d can make the phase between - $(2k + 1)\pi$ and - $(2k + 3)\pi$ when the magnitude of bode diagram > 0 dB, which drives the systems to be stable.

According to (4), the open-loop logarithmic phase frequency characteristics of the system can be yielded as

$$\begin{aligned} &\angle T_g(s)\big|_{s=j\omega} \\ &= \begin{cases} -\omega T_d - \arctan(Cr\omega/(1-CL\omega^2)), (\omega < \omega_{res}) \\ -\omega T_d - \pi - \arctan(Cr\omega/(1-CL\omega^2)), (\omega > \omega_{res}) \end{cases} \end{aligned} \tag{5}$$

Bode diagram of the *CL*-filter at different parasitic resistances is given in Fig. 3. As shown in the figure, the inductive equivalent resistance can only affect the resonance peak of the system, and it has little effect on the phase of the system. Since the resistance of the inductor offers a certain degree of damping and reduces the resonance of the *CL*-filter, which helps stabilizing the system [8]. Therefore, a pure inductance L is considered here to represent the worst case.

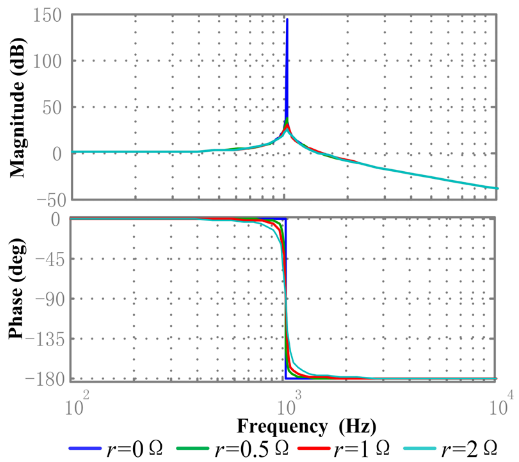


Fig. 3. Bode diagram of *CL*-filter when inductive resistance is considered

From the above analysis process, to avoid any negative crossing at the resonance frequency, the following expression can be derived from (5).

$$\begin{cases} -\omega T_d < -(2k+1)\pi \\ -\omega T_d - \pi > -(2k+3)\pi \end{cases} \tag{6}$$

The time delay stable region can be yielded as

$$\frac{(2k+1)\pi}{\omega_{res}} < T_d < \frac{2(k+1)\pi}{\omega_{res}}, (k = 0,1,2...) \tag{7}$$

The system will be unstable unless T_d is in the above region.

C. Analysis of Inherent Damping Control in Weak Grid Case

The study above aims at the impedance of the grid is zero. However, the grid impedance is not zero in practice [12]. To verifying the stability of inherent damping control, a case of the influence of the weak grid on the inherent damping control is analyzed below.

Considering the grid impedance, the resonance angular frequency of the *CL*-filter ω_{res} can be transformed into

$$\omega_{res} = \sqrt{\frac{1}{(L + L_g)C}} \tag{8}$$

where L_g is the grid-side inductor.

Setting C = 2.5 μF, f_s = 10 kHz. The bode diagram of the CSI in different grid-side inductor case is illustrated in Fig. 4. It can be seen that when the delay time is larger, the phase curve drops faster, and the lag is greater. As the L_g increases, the resonant frequency of CSI is decreases.

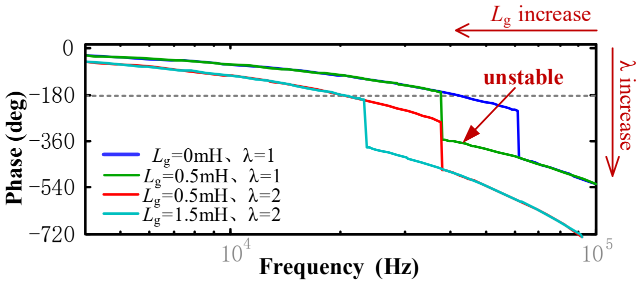


Fig. 4. Bode diagram of the current source converter in weak grid case.

In conclusion, the grid impedance will affect the stability of grid current controlled CSI and could make the inverter unstable. When λ = 1, T_d =1.5T_s. The system can be stable when L_g=0mH, while unstable when L_g=0.5mH. However, adding delay can make the phase curve drop to counteract the effect of grid inductance. When λ = 2, T_d =2.5T_s. The system can be stable under the condition of L_g=0.5mH. Thus, the system can be stabilized by add a reasonable delay.

III. Simulation Results

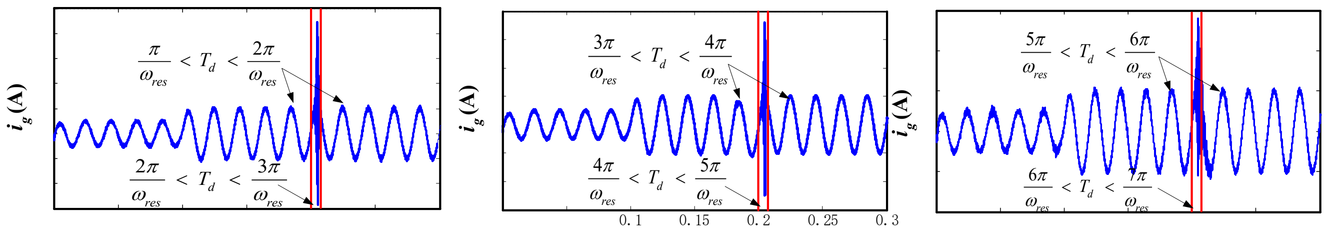
To verify the effectiveness of the proposed stability analysis of time delay, the time-domain simulation test is carried out in Matlab/ Simulink environment and the parameters are shown in Table I. The filter parameters are designed by the general method in [8].

TABLE I. Simulation and Experiment Parameters

Parameters	**Value**
Grid current	5 A/2.5A
DC side current	8 A
DC side inductance (Ldc)	5 mH
Switching frequency	10 kHz
Filter capacitor (C)	9.4 μF
Filter inductor (L)	0.5 mH

For grid current feedback, transient responses when $\pi/\omega_{res}<T_d<2\pi/\omega_{res}$ (k=0), $3\pi/\omega_{res}<T_d<4\pi/\omega_{res}$ (k=1), and $5\pi/\omega_{res}<T_d<6\pi/\omega_{res}$ (k=2) are shown in Fig. 5. At 0.1s, the grid-connected current amplitude steps from 2.5A to 5A. From the simulation results, it can be seen that when the time delay is within the stable range, the grid-connected inverter can be stable without damping. On the other hand, the delay time changes from stable interval to unstable at 0.2s, which are also shown in Fig. 5. The system will be unstable, and resonance occurs. Then, the delay time is switched back to stable value at 0.205s again and the accuracy of the theoretical analysis of delay stability interval is verified.

Combining the results above, it is clear that the system can be stable without additional damping by selecting reasonable delay time. On the contrary, if the delay time is not in the stable interval, the system will not be stable no matter what the regulator parameter is. Although not shown here, the loop can also be made stable when k ≥ 3. However, as can be seen from Fig. 5, for a larger k, a slower transient response is produced because of the lower bandwidth.



(a) (b) (c)

Fig. 5. Simulated transient responses of grid-side current feedback when T_d in different ranges. (a) $\pi/\omega_{res}<T_d<2\pi/\omega_{res}$, $2\pi/\omega_{res}<T_d<3\pi/\omega_{res}$. (b) $3\pi/\omega_{res}<T_d<4\pi/\omega_{res}$, $4\pi/\omega_{res}<T_d<5\pi/\omega_{res}$. (c) $5\pi/\omega_{res}<T_d<6\pi/\omega_{res}$, $6\pi/\omega_{res}<T_d<7\pi/\omega_{res}$.

IV. Conclusion

This paper has studied the relationship between time delay and stability of digital controlled single-loop grid-connected CSI with *CL*-filter. It is found that the time delay is one of the key factors affecting the stability of the grid-connected CSI. Thus, the proposed inherent damping control strategy only requires an appropriate delay in the control loop, avoiding additional damping control, without increasing system costs. In addition, the influence of weak grid case on the inherent damping control is analyzed, and the stability of the control method is verified under a certain range of grid impedance. Both the theoretic analysis and the simulation results have shown that, using the proposed inherent damping control method, the resonant can be suppressed better than with single-loop control scheme alone. Furthermore, the procedure can be extended to analyze the influence of time delay on the stability of *CL*-filtered grid-connected CSI controlled by other methods including active damping. The proposed analysis method has the potential to serve as a general solution to time delay compensation of digitally controlled PWM converter.

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